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Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil

Altamir Mateus Bertollo [a], Moacir Tuzzin de Moraes [b,*], Julio Cezar Franchini [c], Amin Soltangheisi [d,e], Alvadi Antonio Balbinot Junior [c], Renato Levien [a], Henrique Debiasi [c]

[a] Federal University of Rio Grande do Sul, Faculty of Agronomy, Department of Soils, 91540-000, Porto Alegre, RS, Brazil
[b] Federal University of Technology-Paraná, Campus Francisco Beltrão, Department of Agronomic Science, PO Box 135, 85601-970, Francisco Beltrão, PR, Brazil
[c] Embrapa Soybean, PO Box 231, 86001-970, Londrina, PR, Brazil
[d] University of São Paulo, Center of Nuclear Energy in Agriculture, Isotopic Ecology Laboratory, 13416-000, Piracicaba, SP, Brazil
[e] Lancaster Environment Centre, Lancaster University, Lancaster, UK

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ABSTRACT

The impact of soil compaction on soybean root growth and grain yield can be alleviated by the presence of biopores and root channels in the soil profile. We hypothesize that cover crops (ruzigrass and oats) are better than grain crops (wheat and maize) to reduce the soil physical limitation to soybean root growth. We aimed to identify which precrops have higher potential to reduce the mechanical and water stresses resulting from soil compaction and soil desegregation, and to enhance soybean (*Glycine max* L) root growth and yield in an Oxisol (Rhodic Eutrudox), with clayey soil texture. Soybean was grown after four precrops (ruzigrass, oats, wheat, or maize), under four soil compaction levels [soil chiselling (MTC), no-tillage (NT), NT additionally compacted with four passes of a tractor (NTCT), and NT additionally compacted with eight passes of a grain harvester (NTCH)]. Soil physical attributes (bulk density, macroporosity, water-filled pore space and soil penentration resistance) in the soil profile (0−50 cm) and soybean components (grain yield, cumulative root length density and root dry mass) were investigated. Soil physical attributes were improved over time due to the combined effects of natural wetting-drying cycles and biopores created by the roots of precrops. Ruzigrass increased soybean root biomass and length density, mainly at deeper soil layers of compacted treatments (NTCT and NTCH). The rate of increase of soybean root length density in the soil profile was higher after ruzigrass cultivation in comparison with maize and oats. Soil compaction effects on grain yield were partially (NTCH) or totally (NTCT) alleviated after two years and ruzigrass intensified the mitigation process. Ruzigrass also resulted in higher soybean yields in comparison with maize, whereas NTCH and MTC reduced yields in approximately 400 kg ha^{-1} (~13 %) compared to NT and NTCT. Soil strengthening was more evident after ruzigrass and oats cultivation than maize or wheat cropping. Soil compaction in clayey Oxisols can be alleviated over time as a result of root channels provided by precrops combined with natural wetting-drying cycles. Among the evaluated precrops, ruzigrass is of particular interest, as it provides the most suitable soil physical environment for soybean root growth and grain yield. In contrast, chiselling was demonstrated to be a non-viable strategy to mitigate soil physical constraints for root growth and grain yields.

1. Introduction

No-tillage (NT) has long been recognized as one of the most important technologies for soil and water conservation. Currently, NT is adopted in more than 100 million hectares worldwide and more than 32.8 million hectares in Brazil (FEBRAPD, 2019). Agronomic, economic and environmental benefits provided by NT are well-studied (Alvarez and Steinbach, 2009; Engel et al., 2009; Franchini et al., 2012; Fuentes et al., 2009; Lal et al., 2007; Moraes et al., 2016a; Silva et al., 2014). However, compacted soil layers have been detected in areas managed under long-term NT (Alvarez and Steinbach, 2009; Dal Ferro et al., 2014; Nunes et al., 2015) which can be associated to intensive traffic of

* Corresponding author.
E-mail addresses: altamirmateus@gmail.com (A.M. Bertollo), mtmoraes@utfpr.edu.br (M.T. Moraes), soltangheise@gmail.com (A. Soltangheisi), alvadi.balbinot@embrapa.br (A.A. Balbinot Junior), renatole@ufrgs.br (R. Levien), henrique.debiasi@embrapa.br (H. Debiasi).

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heavy agricultural machinery under inadequate soil conditions (Hamza and Anderson, 2005), and also to the adoption of cropping systems with low biodiversity (Abdollahi et al., 2015; Calonego et al., 2017; Moraes et al., 2016a).

Soil structure can be naturally recovered from compaction stresses through wetting–drying cycles (Bonetti et al., 2017); however, crop roots can accelerate this recovery process (Gregory et al., 2007; Tivet et al., 2013). Root growth ameliorates soil structure mainly by biopores formation (Han et al., 2015), which alleviates mechanical and water stress for root elongation (Moraes et al., 2018a). However, quantitative evidences regarding the influence of soil-root interactions on the soil pore system are scarce (Han et al., 2016). Roots elongate more slowly in dry soils due to a combination of water stress and mechanical impedance (Bengough et al., 2011). Adequate root elongation is important for plant growth, especially in soils where water and nutrient availability is limited (Bengough et al., 2011).

Soil compaction can be mitigated by mechanical and biological methods (Nunes et al., 2015; Rosolem and Pivetta, 2017). One biological option to reduce the soil compaction effect on plant development, is the crop root growth (Colombi et al., 2018), especially plants with fibrous and vigorous root systems (Han et al., 2016) capable of penetrating into the subsoil (Kautz, 2015) which can create stable and continuous biopores (Han et al., 2015; Landl et al., 2019). These biopores and channels remain after the decomposition of crop roots (Williams and Weil, 2004) and can be used as preferential growth paths for the roots of the subsequent crop (Bodner et al., 2014), mainly in compacted soils (Romero-Ruiz et al., 2018; Landl et al., 2019), and facilitate water uptake from deep layers (McKenzie et al., 2009). The biopores will also become preferential flow pathways for air and water, which may increase the overall soil saturated hydraulic conductivity (Yu et al., 2016) by several orders of magnitude, thereby, increasing water and oxygen availability for plant roots (Romero-Ruiz et al., 2018). These root channels may additionally facilitate formation of biological hotspots (Romero-Ruiz et al., 2018).

We hypothesised that cover crops (ruzigrass and oats) are better than grain crops (wheat and maize) with regards to reducing the soil physical limitation to help soybean root growth. **We** aimed to identify which precrops have higher potential to reduce the mechanical and water stresses resulting from soil compaction and soil desegregation, and to enhance soybean root growth and yield in an Oxisol (Rhodic Eutrudox), with clayey texture.

2. Material and methods

2.1. Site description and experiment establishment

This experiment has been conducted in an area under NT since 1991 at the Experimental Station of Embrapa Soybean, in Londrina (latitude 23°12′S; longitude 51°11′W; and 585 m altitude) State of Paraná, Southern Brazil. According to the Köppen classification, the climate of the region is humid subtropical (*Cfa*), with an annual average temperature of 21 °C, and maximum and minimum temperatures of 28.5 °C (in February) and 13.3 °C (in July), respectively. The average annual precipitation is 1651 mm, with January being the wettest (217 mm) and August the driest (60 mm) months (Alvares et al., 2013). The soil was an Oxisol (Latossolo Vermelho Distroférrico, Brazilian classification; Rhodic Eutrudox, USA classification), with clayey soil texture (i.e. having clay content of 791 g kg^{-1}, silt content of 139 g kg^{-1}, and sand content of 70 g kg^{-1} in 0–50 cm depth) (Table 1). Data of textural composition from 30 to 50 cm depth were obtained by Ortigara (2017). Soil particle density at 0–50 cm depth is 2.96 Mg m^{-3}, and the mean slope of the experimental area is 0.03 m m^{-1}.

Before the establishment of the experiment, from 1991 to 2009, the area was managed under a crop rotation system comprising soybean (*Glycine max* L. Merril) or maize (*Zea mays* L.) in the summer, and wheat (*Triticum aestivum* L.) or black oat (*Avena strigosa* Schreb) in the winter.

Table 1
Soil chemical and particle-size characterization of the experimental area after the compaction levels establishment in 2013.

Soil attribute	Soil compaction level																			
	MTC	NT	NTCT	NTCH	MTC	NT	NTCT	NTCH	MTC	NT	NTCT	NTCH	MTC	NT	NTCT	NTCH	MTC	NT	NTCT	NTCH
	Soil layer (cm)																			
	0–10 cm				10–20 cm				20–30 cm				30–40 cm				40–50 cm			
C (g kg^{-1})	16.1	16.0	16.0	14.6	11.1	10.6	10.1	10.9	8.9	9.4	8.8	9.0	5.9	6.2	6.9	6.1	5.1	5.4	5.6	5.4
P (mg dm^{-3})	20.0	30.1	17.1	26.5	9.1	7.9	7.7	10.7	4.8	4.5	4.3	5.0	3.5	3.6	3.4	3.1	3.3	3.4	3.1	3.2
K ($cmol_c$ dm^{-3})	0.4	0.4	0.5	0.7	0.5	0.3	0.4	0.6	0.3	0.2	0.4	0.4	0.2	0.1	0.3	0.3	0.2	0.1	0.2	0.2
Calcium ($cmol_c$ dm^{-3})	3.5	3.8	4.0	3.7	2.1	2.2	2.9	2.4	2.1	2.5	3.1	2.7	2.5	3.0	3.2	3.0	2.6	2.9	3.2	3.1
Mg ($cmol_c$ dm^{-3})	1.7	2.1	1.8	1.8	0.9	1.0	1.1	1.0	0.6	0.7	0.8	0.8	0.5	0.7	0.7	0.7	0.5	0.7	0.7	0.7
pH ($CaCl_2$)	5.0	5.2	5.3	5.2	4.7	4.8	5.0	4.9	4.8	4.9	5.2	5.1	5.0	5.1	5.4	5.4	5.0	5.2	5.6	5.4
Al ($cmol_c$ dm^{-3})	0.1	0.0	0.0	0.0	0.3	0.3	0.1	0.2	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H + Al ($cmol_c$ dm^{-3})	5.2	4.6	4.6	4.6	5.7	5.5	4.9	5.0	5.0	4.7	4.2	4.4	4.0	4.1	3.6	3.7	3.9	3.6	3.1	3.5
CEC_{pH7} ($cmol_c$ dm^{-3})	10.8	10.9	10.9	10.7	9.2	9.0	9.3	8.9	8.1	8.1	8.4	8.4	7.3	7.9	7.7	7.6	7.2	7.2	7.2	7.4
$CEC_{effective}$ ($cmol_c$ dm^{-3})	5.7	6.3	6.3	6.1	3.8	3.7	4.5	4.1	3.3	3.5	4.3	4.1	3.3	3.8	4.1	3.9	3.3	3.6	4.0	3.9
Clay (g kg^{-1})	763	756	776	773	804	785	789	790	801	789	795	790	798[a]				806[a]			
Silt (g kg^{-1})	163	173	142	161	136	146	134	131	138	144	128	134	138[a]				126[a]			
Sand (g kg^{-1})	74	71	82	66	60	69	77	79	61	67	77	76	64[a]				68[a]			

*Data represent the average of three replicates. [a] Data of particle size distribution (clay, silt and sand) at the 30–40 and 40–50 cm depth are from Ortigara (2017). C: Soil organic carbon; P: Phosphorus; K: Potassium; Mg: Magnesium; pH $CaCl_2$: potential de hydrogen in solution of $CaCl_2$ 0.01 mol L^{-1} (1:2.5) - active acidity; Al: Aluminum. H + Al: potential acidity; CEC_{pH7}: potential cations exchange capacity; $CEC_{effective}$: effective cations exchange capacity. MTC: minimum tillage system with soil chiselling; NT: no-tillage system; NTCT: no-tillage with additional compaction with four tractor passes; NTCH: no-tillage with eight harvester passes.

In the years 2010–2012, the area was cropped with ruzigrass (*Urochloa ruziziensis* R. German & Evrard) without grazing, which was desiccated with glyphosate at 90 and 20 days before trial establishment in 2013.

Soil chemical and physical characteristics were evaluated, each 10 cm until 50 cm depth, depth after applying different levels of soil compaction in 2013 (Table 1). The soil chemical attributes (pH in $CaCl_2$, available P, K^+, Ca^{2+}, Mg^{2+}, and Al^{3+}) were determined by the methods described in Teixeira et al. (2017). In addition, we calculated the effective ($CEC_{effective}$) and potential ($CEC_{pH7.0}$) soil cation exchange capacity (CEC) for all compaction levels (Table 1).

2.2. Experimental design and treatments

The experiment was laid out in a randomized block split-plot design, with four precrops as the main plots, and four compaction levels as subplots, with three replications (Fig. 1). Thus, there was 48 subplots (4 compaction levels, 4 precrops, and 3 blocks), with a size of 75 m^2 each plot (5 m wide and 15 m length). The area was under No-Tillage since 1991 (22 years) (Fig. 1). Soil compaction and soil chiselling were performed in February 2013. The soil gravimetric water content during the tractor and harvester traffic was equivalent to field capacity (0.34 kg kg^{-1}). The soil compaction levels are described below:

(i) The first compaction level was performed by soil chiselling, referred to as Minimum Tillage with Chiselling (MTC). Soil chiselling in this treatment was performed when the soil was friable (gravimetric water content of 0.29 kg kg^{-1} at 0–20 cm soil layer), using a chisel plow equipped with five shanks spaced 35 cm from each other, and a shank tip of 8 cm of width, working at 25 cm depth.

(ii) The second compaction level was the control under No-Tillage system (NT).

(iii) The third compaction level was performed by tractor traffic, referred to as No-Tillage with additional Compaction by four Tractor passes (NTCT). The additional compaction on this treatment was performed with a tractor (CBT 8060 model) 4 × 2 with front-wheel assist drive (FWA) operating on traffic surface with the FWA engaged, 71 kN of total weight (29 kN on the front axle and 42 kN on the rear axle), equipped with tyres Goodyear 14.9–24 R1 (diagonals) in the front axle (inflation pressure of 120 kPa), and 18.4–34 R1 (diagonals) in the rear axle (inflation pressure of 115 kPa). The recommended tyre inflation pressure for that tyre and load were 170 and 120 kPa for front and rear tyres, respectively. The contact area calculated as proposed by Keller (2005) were 0.22 and 0.34 m^2, for the front and rear tyres, respectively. The maximum vertical stress, calculated according to Keller (2005) were 192 kPa in the front wheel and 181 kPa in the rear wheel. The theoretical mean ground pressure for the contact area calculated as Schjønning and Lamandé (2010) were 132 kPa in the front wheel and 123 kPa in the rear wheel.

(iv) The fourth compaction level was performed by harvest traffic, referred to hereafter as No-Tillage with additional Compaction by eight Harvester passes (NTCH). Soil compaction in this treatment was performed using a self-propelled grain harvester (SLC 7200 model), total weight of 93 kN (68 kN on the front axle and 25 kN on the rear axle) equipped with single front tyres, Pirelli 23.1–30 R1, diagonals, inflated to pressure of 140 kPa; and rear tyres Pirelli 9.00–16 F2 10PR, diagonals, inflated to a pressure of 310 kPa. The recommended tyre inflation pressure for that tyre and load were 140 and 300 kPa for front and rear tyres, respectively. The contact area calculated as proposed by Keller (2005) were 0.39 and 0.09 m^2, for front and rear tyres, respectively. The maximum vertical stress (Keller, 2005) was 217 kPa in the front wheel and 393 kPa in the rear wheel. The theoretical mean ground pressure for the contact area calculated as Schjønning and Lamandé (2010) were 174 kPa in the front wheel and 277 kPa in the rear wheel.

The post-compaction or post-chiselling soil management for all the treatments was no-tillage. After the application of the compaction levels, plots were cultivated with wheat in winter 2013 and soybean in summer 2013/14 (Fig. 1a), using a tractor-pulled planter with row spacing of 17 cm and 45 cm, respectively. In sequence, precrops consisting of ruzigrass, maize, black oat, and wheat (*Triticum aestivum*) were cultivated in the main plots in winter 2014 (Fig. 1a).

2.3. Crop sowing and management

On 20 February 2014, after soybean harvest (2013/2014 cropping season), the vegetation in the area was desiccated with glyphosate (at a

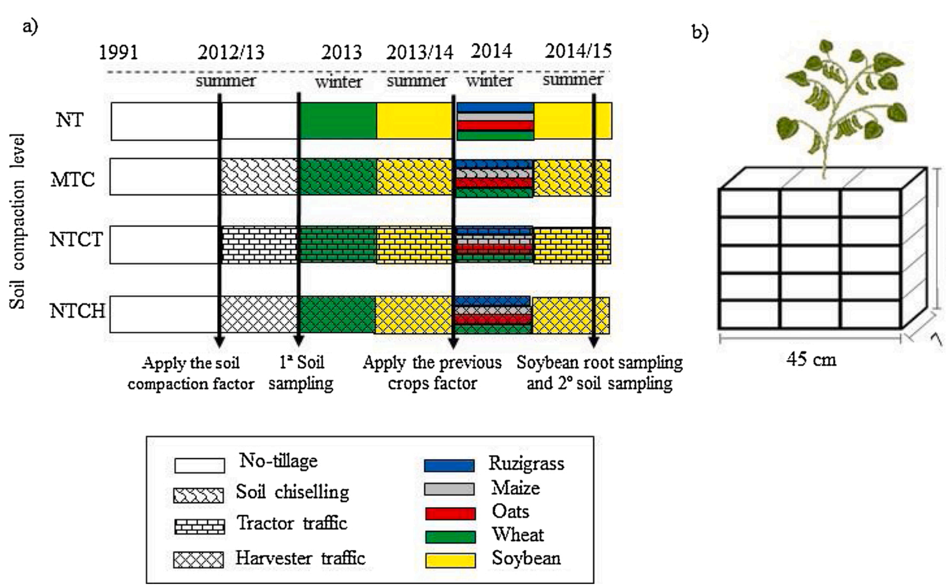

Fig. 1. Schematic representation showing the chronological sequence of management practices, treatment applications, and soil and root samplings in the experiment (a), and the arrangement for soybean root sampling through soil-root monoliths. NT: no-tillage system; MTC: minimum tillage system with soil chiselling; NTCT: no-tillage with additional compaction with four tractor passes; NTCH: no-tillage with eight harvester passes.

dose of 720 g a.e. ha^{-1}) mixed with mineral oil (0.5 l ha^{-1}). Maize (hybrid AG 9010) was sown on 27 February 2014 with a tractor-pulled planter comprising three rows at 90 cm spacing, shanks and double-disks as furrow openers for fertilizer and seed deposition, respectively, helical fertilizer metering mechanism, and horizontal plates with round holes as seed meters. The planter was set to distribute 7 seeds m^{-2} at 5 cm depth, aiming to establish 6 seedlings m^{-2}, and 300 kg ha^{-1} of fertilizer (NPK 08-20-20) at the bottom of a 12 cm- depth furrow. The species ruzigrass, black oat and wheat were also mechanically sown, using a tractor-pulled planter equipped with 13 rows at 17 cm spacing, double-disks as furrow openers for fertilizer and seed deposition, helical fertilizer metering mechanism, and fluted wheels for seed metering. Ruzigrass and black oat were sown on 28 February and 30 April 2014, respectively. Wheat was fertilized with 270 kg ha^{-1} of NPK 8-20-20, applied simultaneously with sowing at the same furrow. Ammonium sulphate was applied to the soil surface as a side dressing to wheat and maize plots at rates of 200 and 400 kg ha^{-1}, respectively (40 and 80 kg N ha^{-1}) 33 days after seedling emergence. The cover crops (ruzigrass and black oat) were not fertilized. The planter was adjusted to distribute 350 seeds m^{-2} at 3 cm depth for wheat and black oat aiming densities of 300 plants m^{-2}, and 95 seeds m^{-2} for ruzigrass, to establish 40 plants m^{-2}.

Maize and wheat were mechanically harvested on 6 August and 15 September 2014, respectively, and their residues were chopped and uniformly distributed over the soil surface. Ruzigrass and black oat were desiccated with glyphosate (1.440 and 720 g a.e. ha^{-1}, respectively) mixed with mineral oil (0.5 l ha^{-1}) on 28 August and 18 September 2014, respectively. Weeds naturally grown in all plots were chemically managed (glyphosate, 540 g a.e. ha^{-1}) on 1 October 2014. Soybean (cultivar BRS 359RR) was sown on 10 October 2014, using a tractor-pulled planter equipped with seven rows at 45 cm spacing, shanks and double-disks as furrow openers for fertilizer (fertilizer metering mechanism with feed screw) and seed deposition (precision vacuum seeder with vertical plates). The seeder was adjusted to distribute 37 seeds m^{-2} at 5 cm depth, aiming the establishment of 30 seedlings m^{-2}. The fertilizer (NPK 0-20-20) was applied at a rate of 270 kg ha^{-1}, in the bottom of a 12 cm deep furrow.

The planting, crop management and the control of weeds, pests and diseases followed the technical recommendations for soybean, maize, wheat, black oat, and ruzigrass, and it was the same for all treatments.

2.4. Soil sampling

Soil sampling was performed in two different times: i) the first sampling was performed at the beginning of the experiment (after soil compaction or chiselling) in February 2013; ii) the second sampling was performed in January 2015 during the soybean cropping, after precrops (Fig. 1a). Undisturbed soil cores (internal diameter and height of 5.0 cm) were collected from five soil layers at 10 cm depth intervals (0–10, 10–20, 20–30, 30–40, and 40–50 cm), and from three different positions (crop rows, the left, and the right side of inter-rows). The first sampling comprised 12 plots (four compaction levels x 3 repetitions), totalling 180 soil cores. In the second sampling, all 48 plots were sampled, totalling 720 samples. The cores were sampled at soil water content near field capacity with a soil sampler apparatus coupled with a tractor, enabling the vertical penetration of the core into the centre of each soil layer.

2.5. Determination of soil physical and hydraulic properties

Soil samples were submitted to a matric potential of −6 kPa on a tension table to perform the soil penetration resistance test. After soil sample reaching to the hydrostatic equilibrium, the soil penetration resistance (SPR) was measured with a lab penetrometer (Moraes et al., 2014). The soil cores were then weighed and oven-dried at 105 °C for 48 h to quantify the soil bulk density (Mg m^{-3}) and volumetric soil water content (m^3 m^{-3}). The soil total porosity (m^3 m^{-3}) was obtained by the relationship between bulk density and soil particle density (2.96 Mg m^{-3}), while the macroporosity (pores >50 mm) was calculated as the difference between total porosity and soil microporosity (pores <50 mm, equivalent to water content at $\Psi = -6$ kPa, equilibrated on a tension table). Water-filled pore space was calculated as microporosity divided by total porosity.

2.6. Grain yield and root growth sampling

Soybean grain yields were evaluated by mechanical harvest of 12 m of six central rows within each subplot, corresponding to a total area of 32.4 m^2. The seeds were cleaned, weighed, and the values obtained were adjusted to 13 % moisture content.

Root system sampling was performed on 5 January 2015, 87 days after soybean sowing. Soil monoliths (50 cm depth x45 cm wide x7 cm thick) were taken from trenches perpendicular to the soybean rows, opened in all 48 subplots (Fig. 1b). Each monolith was divided into five depths (0–10, 10–20, 20–30, 30–40, and 40–50 cm) and three widths of 15 cm each, resulting in 15 soil blocks for each monolith (Fig. 1b). Soybean roots were then separated from the blocks and water was used to wash away the soil through a 500 μm sieve (Böhm, 1979)

The root length in each soil block was measured by scanning of 10 % of dry root mass and then correlating it to the total dry root mass of the soil block. Root scanning was performed with a scanner (Delta-T Scan) followed by images processing with the software Safira 2.0 (Jorge and Silva, 2010) for analysis of fragments and roots. Root length density was calculated as the ratio of root length to soil volume. Root dry biomass was determined after oven-drying at 60 °C for five days and then related to soil surface area or soil volume.

2.7. Data analysis

The data of soil attributes (bulk density, macroporosity, water-filled pore space and SPR) and plant responses (grain yield, cumulative root length density and dry mass) were subjected to analysis of variance (ANOVA) using PROC GLM to test the effect of precrops and compaction levels. Each soil layer was analysed separately for testing soil and root parameters. When the effects of treatments were significant ($P < 0.05$), means were compared with Fisher's least significant difference test ($P < 0.10$).

Independently of soil layers, SPR models were obtained by fitting SPR values to bulk density and water content separately for each precrop, using the non-linear model (eq. 1) described by Busscher (1990). The Busscher model was fitted to the measured data using the routine "PROC NLIN" following the Gauss-Newton method from the Statistical Analysis System 9.4 - SAS (SAS Institute Inc., 2013), and the graphs plotted through the program SigmaPlot®12.5 (Systat software, Inc.).

$$SPR = aBD^b\theta^c \quad (1)$$

where SPR is the soil penetration resistance (MPa); BD is the bulk density (Mg m^{-3}); θ is the soil volumetric water content (m^3 m^{-3}); a, b and c are fitting parameters of the model.

SRP models were compared among precrops using the area under the curve, calculated by the integral of the model, considering water content and bulk density values ranging from 0.36 to 0.46 m^3 m^{-3} and 1.15 to 1.40 Mg m^{-3}, respectively. These intervals comprise the common values for all the treatments at field condition. Areas under the curves were calculated with numerical integration considering the portions based on Vectorized adaptive quadrature (quadva) routine (Shampine, 2008) using the Matlab® software. The integral values were subjected to ANOVA test ($P < 0.05$) and, whenever F-values were significant ($P < 0.05$), means were compared by Tukey test ($P < 0.05$). All data analyses were performed using the software Statistical Analyses System (SAS Institute Inc., 2013).

3. Results

3.1. Soil physical attributes

The interaction between precrops and soil compaction levels influenced the soil structure through the soil profile (Figs. 2 and 3). Except for MTC, bulk density values at 0−30 cm depth in January 2015 (after precrops) were generally lower than in February 2013 (before precrops), and this effect was even clearer for the uppermost layer (0−10 cm) under additionally compacted treatments (NTCT and NTCH) (Fig. 2). Conversely, bulk density at 30−50 cm layers usually increased after precrops regardless of the compaction level. Higher bulk density before precrops compared to after them at 0−10 cm layer was also observed under MTC (Fig. 2a). The alteration of the bulk density values between sampling dates was crop-dependent; at 0−10 cm depth, bulk density differences among different precrops were small except for NTCH, where lower values were observed for ruzigrass and wheat (Fig. 2h). However, ruzigrass usually resulted in higher bulk density at deeper layers, mainly at 30−50 cm depth under MTC, NT and NTCT.

Precrops associated with wet-dry cycles enhanced soil macroporosity under different compaction levels (Fig. 3f, g, h) compared to the previous conditions in 0−30 cm soil depth, except under MTC (Fig. 3e) whose soil macroporosity was not influenced by precrops in 0−20 cm soil depth. Under MTC, macroporosity was enhanced by precrops at 20−30 soil depth compared to the previous condition (MTC before crop cultivation). We cannot differentiate among precrops for modifying macroporosity under NT (Fig. 3f) and NTCT (Fig. 3g), and it can be stated that all of them acted very well in enhancing macroporosity especially in the soil surface layer (0−10 cm), while under NTCH (Fig. 3f), ruzigrass and wheat were more effective related to oats and maize in the same soil layer.

Precrops decreased the percentage of water-filled pore spaces (WFPS) under different compaction levels (Supplementary Figs. S1f, S1g, S1h) in comparison with the previous conditions in 0−30 cm soil depth, except under MTC (Supplementary Fig. S1e) which WFPS were increased by precrops in 0−10 and 20−30 cm soil depths.

3.2. Soil penetration resistance curves

Soil penetration resistance (SPR) models were clearly influenced by precrops (Table 2 and Fig. 4). Under a given combination between bulk density and water content values, SPR was higher after precrops, evidencing a time-mediated soil strengthening process. Additionally, the relative increase in SPR from February/2013 to January/2015 was strongly associated to the precrops (Fig. 4b). Cover crops (oats and ruzigrass) enhanced SPR by 50 % compared to before precrops whereas this increase was around 30 % under grain crops (maize and wheat). The effect of cover crops on improving soil strength was intensified with increasing bulk density, while the reverse trend was observed under grain crops (Fig. 4b). Corroborating these results, the area under the curve was increased by 43 % averaged among precrops compared to before them. The area under the curve was also influenced by different precrops, being higher under cover crops (ruzigrass and oats) in comparison with grain crops (maize and wheat) (Table 2).

3.3. Soybean root growth

Soybean root length density (Fig. 5) and root dry biomass (Fig. S2) were affected by the interaction between precrops and soil compaction levels. Under MTC, oat was the most successful crop to improving the soil quality (i.e., physical, chemical or biological quality) for soybean root growth (Fig. 5e) and consequently higher root biomass at all depths evaluated (Fig. S2e). Precrops did not influence neither soybean root length density under MTC (Fig. 5e) nor root dry mass of soybean cultivated under NT (Fig. S2f). However, the positive effects of Ruzigrass were shown under the most compacted treatments [NTCT (Fig. S2g) and NTCH (Fig. S2 h)], ruzigrass enhanced soybean root dry biomass (Figs. S2g nd S2h) and root length density in deep soil layers (0–40 and 0−50 cm) in NT (Fig. 5f). Both wheat and ruzigrass resulted in greater root length density under NTCT (Fig. 5g), whereas ruzigrass had the most positive effect under NTCH (Fig. 5h).

The beneficial influence of precrops on soybean root length density at deeper soil layers intensified with increasing the compaction level. The rate of increase of soybean root length density in the soil profile was higher after ruzigrass cultivation in comparison with maize and oats (Table 3). Conversely, the intercept was not significantly influenced by precrops, showing that the positive effects of ruzigrass on soybean root length density in relation to the other crops were stronger at deeper soil layers. The NT system promoted higher root growth in the soil profile relative to MTC and NTCT, and higher intercept values compared to MTC (Table 3).

Soybean root system distribution in 2D was affected by precrops and

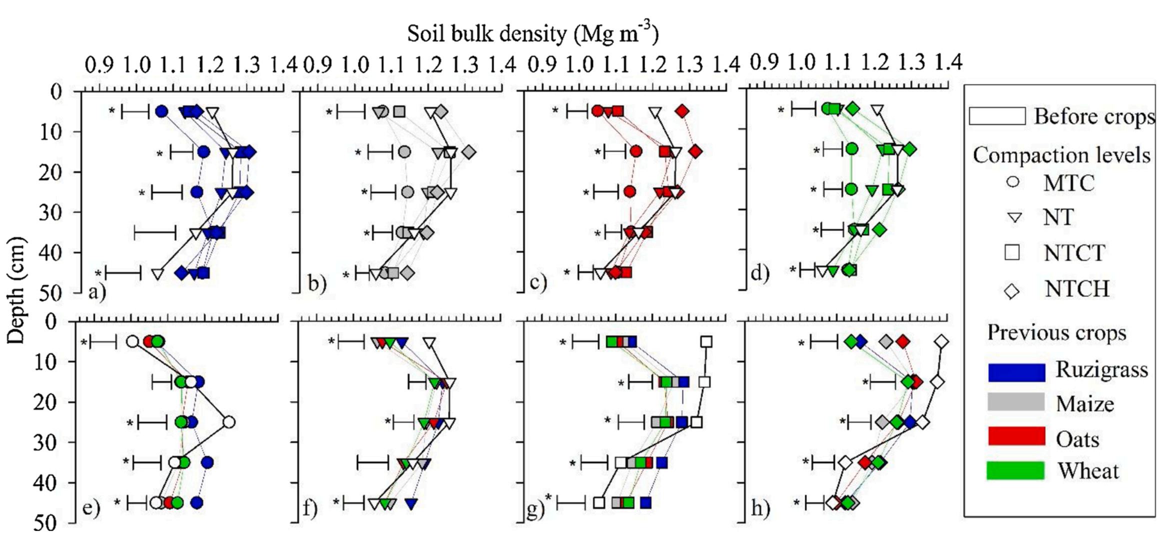

Fig. 2. Soil bulk density in the soil profile before and after previous crops (ruzigrass (a), maize (b), oats (c), and wheat (d)) under different compaction levels (minimum tillage with chiselling - MTC (e), no-tillage - NT (f), no-tillage compacted with four traffic of tractor - NTCT (g) and no-tillage compacted by eight passes of harvest - NTCH (h)) in an Oxisol. Bars represent the values of least significant difference by Fisher's exact test, when followed by * the differences between treatments are significant ($p < 0.05$).

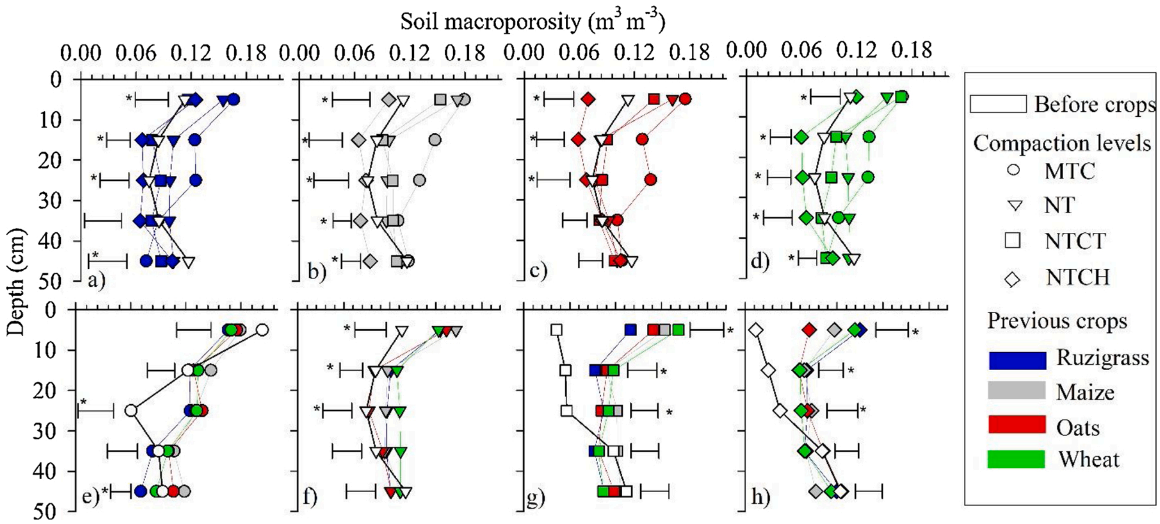

Fig. 3. Soil macroporosity in the soil profile before and after previous crops (ruzigrass (a), maize (b), oats (c), and wheat (d)) under different compaction levels (minimum tillage with chiselling - MTC (e), no-tillage - NT (f), no-tillage compacted with four traffic of tractor - NTCT (g) and no-tillage compacted by eight passes of harvest - NTCH (h)) in an Oxisol. Bars represent the values of least significant difference by Fisher's exact test, when followed by * the differences between treatments are significant ($p < 0.05$).

Table 2
Empirical parameters fitted to the models of soil penetration resistance and integral of the equations (area under curve) as affected by precrops in an Oxisol.

Previous crop	SPR model[I]	R^2	Area under the curve[II]
Before cropping at 2013	$0.2945\ BD^{5.0741}\ \theta^{-0.5252}$	0.96*	0.165 C
Ruzigrass	$0.3640\ BD^{5.7965}\ \theta^{-0.5070}$	0.92*	0.246 A
Maize	$0.5835\ BD^{4.9363}\ \theta^{-0.0932}$	0.93*	0.218 B
Oats	$0.3182\ BD^{5.5228}\ \theta^{-0.7787}$	0.95*	0.255 A
Wheat	$0.4188\ BD^{4.8325}\ \theta^{-0.5426}$	0.94*	0.227 B

[I]soil penetration resistance model: SPR = $a{*}BD^{b}{*}\theta^{c}$; BD: bulk density (Mg m^{-3}); θ: soil water content ($m^3\ m^{-3}$); R^2= [1-(SQerror/SQmodel)]; *significant at 5% level of probability by F-test; [II]means followed by the same letter did not differ at 5% level of probability by Tukey test.

compaction levels (Fig. 6). As expected, soybean root biomass usually concentrated beneath the crop row regardless of depth and treatments (Fig. S3), which is explained by the tap root position (high biomass but low area). However, root biomass concentration was generally higher under MTC, mainly in the plots cultivated with ruzigrass (Fig. S3a-i). For instance, soybean root biomass values were ~2400 and 470 g m^{-3} in the row (from −7.5 to +7.5 cm of plant stem) and inter-row (from ±7.5 to ±22.5 cm of plant stem), respectively, under no-tillage (NT) (Fig. S3a-i), reduced to ~1500 and 240 g m^{-3} under MTC (Fig. S3b-i). Conversely, root length density presented a more uniform horizontal distribution from the soybean row for all depths and treatments (Fig. 6), indicating a similar potential for water and nutrient uptake from row and inter-row. Interestingly, ruzigrass cultivation under NT (Fig. 6b-i) and additionally compacted treatments (Fig. 6c-i and d–i) consistently led to higher values of soybean root length density near the centre of inter-row, mainly up to 30 cm depth.

Soybean roots penetrated to deeper soil layers in areas previously cultivated with ruzigrass under NT (Figs. 6b-I and S3b-i), NTCT (Figs. 6b-i and S3c-i), and NTCH (Figs. 6S3d-i) compared to the other precrops. Soybean cultivated after oats in compacted soils also presented

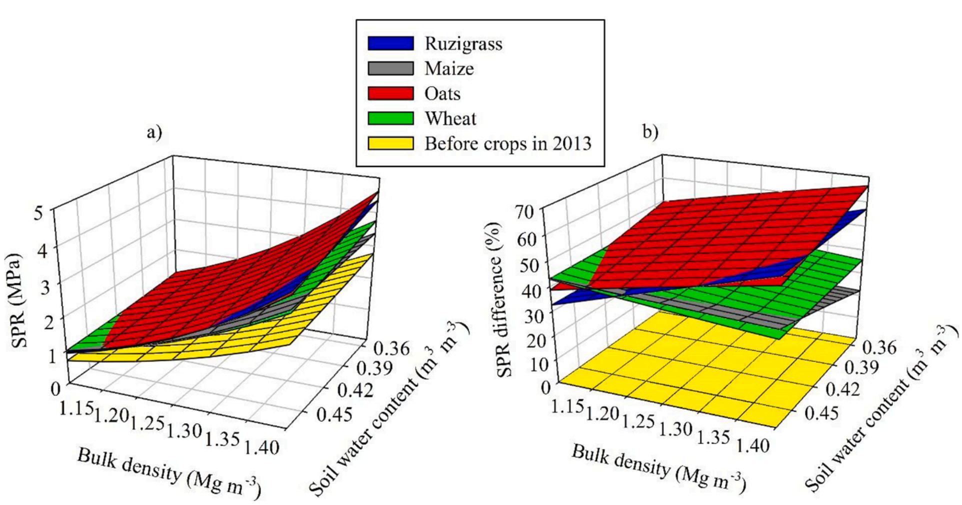

Fig. 4. Soil penetration resistance (SPR) curves as a function of soil water content and bulk density influenced by precrops (a) and its relative difference from the beginning of the experiment in 2013 (before precrops) (b) in an Oxisol.

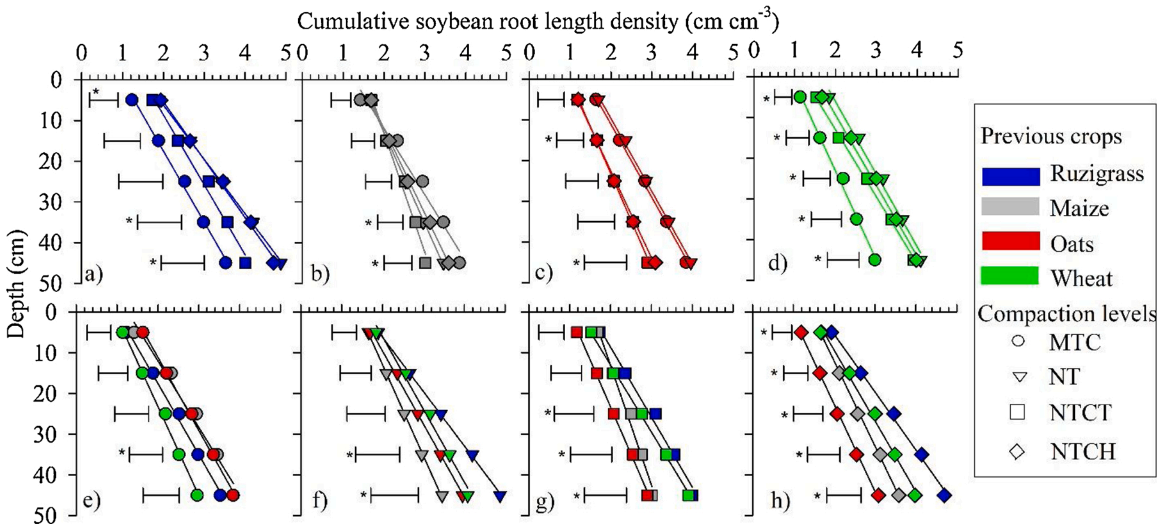

Fig. 5. Cumulative soybean root length density in soil profile affected by previous crops (ruzigrass (a), maize (b), oats (c), and wheat (d)) under different compaction levels (minimum tillage with chiselling - MTC (e), no-tillage - NT (f), no-tillage compacted with four traffic of tractor - NTCT (g) and no-tillage compacted by eight passes of harvest - NTCH (h)) in an Oxisol. Bars represent the values of least significant difference by Fisher's exact test ($p < 0.10$), when followed by * the differences between treatments are significant.

Table 3
Rate of increase of root length density per cm of soil depth (slope of linear regression) for simple effects of previous crops and compaction levels at the soil profile (0-50 cm depth, see also Fig. 7).

Simple effects	Rate of RLD increases[1] (cm cm^{-3})	Std Dev	intercept	Std Dev
Previous crop				
Ruzigrass	0.065 a	0.019	1.420 ns	0.646
Maize	0.046 b	0.014	1.428	0.289
Oats	0.050 b	0.016	1.196	0.527
Wheat	0.055 ab	0.014	1.327	0.416
Compactions levels				
MTC	0.054 b	0.009	1.161 b	0.451
NT	0.058 a	0.024	1.522 a	0.475
NTCT	0.049 b	0.016	1.321 ab	0.512
NTCH	0.056 ab	0.016	1.367 ab	0.477

RLD: root length density; [1]slope from linear regression ($y = a*x + b$) between cumulative root length densities in soil profile and soil depth. *Means followed by the same letter do not differ by the Fisher's exact test ($p < 0.10$). ns: non-significant. MTC: minimum tillage system with soil chiselling; NT: no-tillage system; NTCT: no-tillage with additional compaction with four tractor passes; NTCH: no-tillage with eight harvester passes.

reduction of root dry mass (Figs. S3c-iii and S3d-iii) and root length density (Fig. 6c-iii and d-iii) at the topsoil (0−10 cm depth) in relation to the sites cultivated with ruzigrass. MTC resulted in reduced soybean root growth in the entire soil profile (Figs. 6a and S3a) compared to NT (Figs. 6b and S3b). Considering ruzigrass as precrop, MTC led to smaller soybean root biomass (Figs. S3a-i and S3a-iv) and length (Fig. 6a-i and a-iv) even when compared to NTCH (Figs. 6 and S3 d-i). The same effect was observed for wheat (Figs. 6d-iv and S3d-iv) at 0−20 cm layer.

3.4. Precrops alleviate soybean grain yield losses induced by soil compaction

Soybean grain yield was influenced by the precrops (Fig. 7a) and soil compaction levels (Fig. 7b), but not by their interaction. The highest soybean grain yield was obtained after ruzigrass, significantly higher than after maize cropping (Fig. 7a). Soybean grain yield was lower under MTC and NTCH in comparison with NT and NTCT (Fig. 7b), which did not differ from each other. It has to be highlighted that the yield losses due to heavy soil compaction (NTCH) and chiselling (MTC) were similar (~400 kg ha^{-1}).

4. Discussion

Our results showed significant reductions of soil compaction under the most compacting treatments (NT, NTCT, and NTCH) (i.e, lower bulk density and greater macroporosity) by the cultivation of all precrops evaluated before soybean cultivation at 0−20 cm depth (Figs. 2 and 3). Values of bulk density, macroporosity and water-filled porosity after precrops were similar to those measured for NT at the start of the experiment, representing the initial condition of the experimental area.

There were small differences in bulk density, macroporosity and water-filled porosity among the precrops evaluated (Figs. 2, 3 and S1), in spite of the wide variation in their capacity to produce roots and shoots and hence, to reduce the level of soil compaction (Moraes et al., 2016b). This result can be ascribed mainly to the low sensitivity of physical attributes based on mass/volume relations (e.g., bulk density and macroporosity) to detect alterations on soil structure promoted by plants, as previously reported by Dal Ferro et al. (2014) and Moraes et al. (2016a). Simultaneously, root growth of the precrops contributes to fracture compacted layers (Gregory et al., 2007) and creates a complex network of continuous and stable biopores (Perkons et al., 2014; Rosolem and Pivetta, 2017; Wuest, 2001), thus improving soil structure mainly by altering the pore size distribution (Leitner et al., 2014). Moreover, precrops provide the addition of root and shoot biomass, root exudates and soil mulching, leading to a favourable soil environment to macrobiota (Wuest, 2001) and microbiota functioning (Silva et al., 2010), which in turn result in a better soil aggregation and structural quality (Moraes et al., 2017; Naveed et al., 2017).

All precrops increased SPR in a certain bulk density and water content related to the values before their cultivation in February/2013, but this increase was higher for cover crops (ruzigrass and oats) compared to grain crops (maize and wheat) (Table 2 and Fig. 4). Soil strengthening over time, without significant alterations in bulk density and water content, results from the age-hardening process (Utomo and Dexter, 1981) in highly-wheatered tropical soils under long-term NT (Moraes et al., 2019b, 2017). It is important to highlight that aggregate strengthening over time is usually an advantageous process, increasing soil resistance against disruptive forces, e.g. the pressures applied by agricultural machinery wheels (Moraes et al., 2019b).

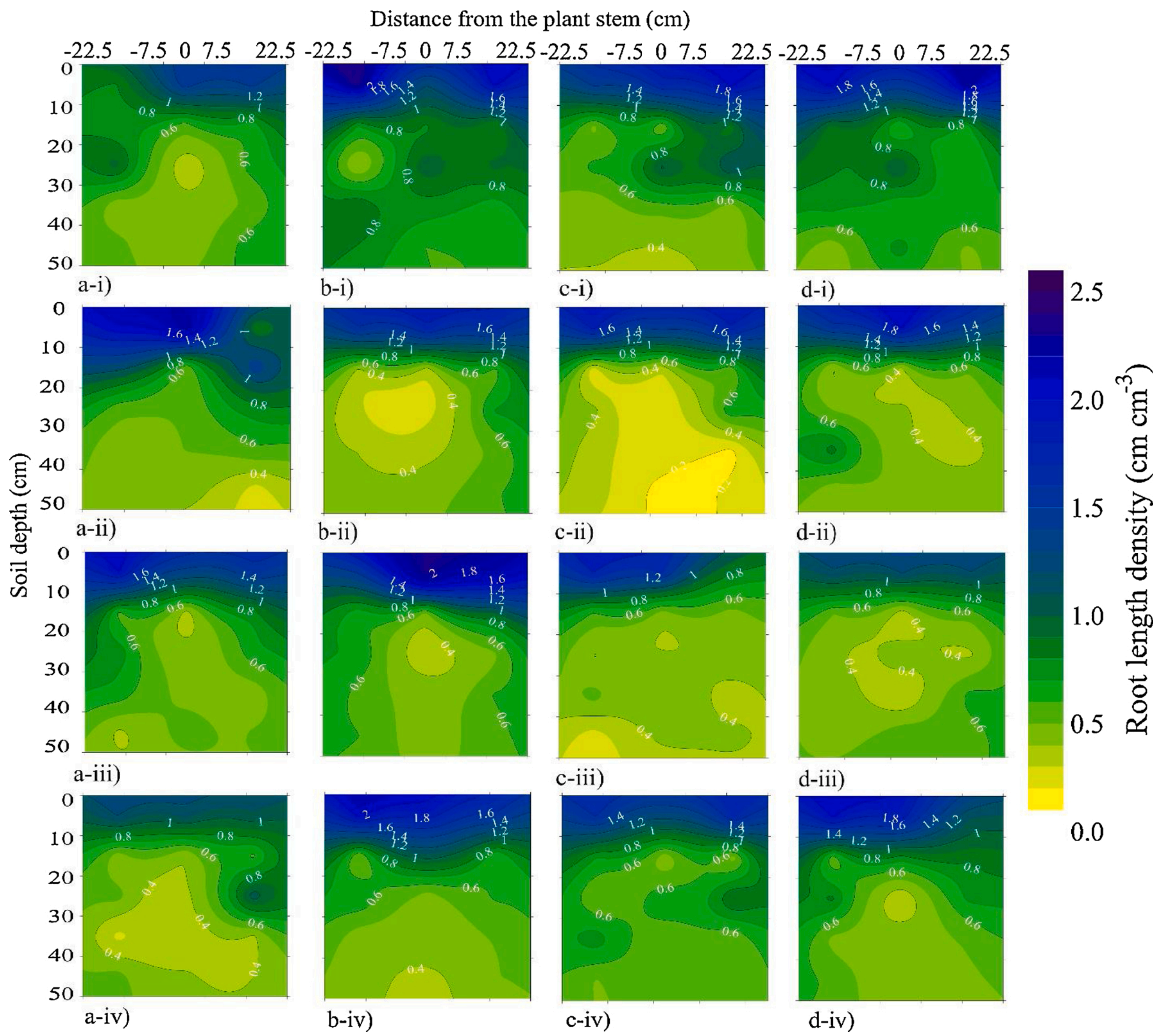

Fig. 6. 2D distribution of soybean root length density in soil profile under four soil compaction levels of soil chiselled (MTC) (a), no-tillage (NT) (b), no-tillage compacted by four tractor passes (NTCT) (c) and no-tillage compacted by eight harvest traffic (NTCH) (d), previously cultivated with four precrops, i.e. ruzigrass (i), maize (ii), oats (iii) and wheat (iv) in an Oxisol.

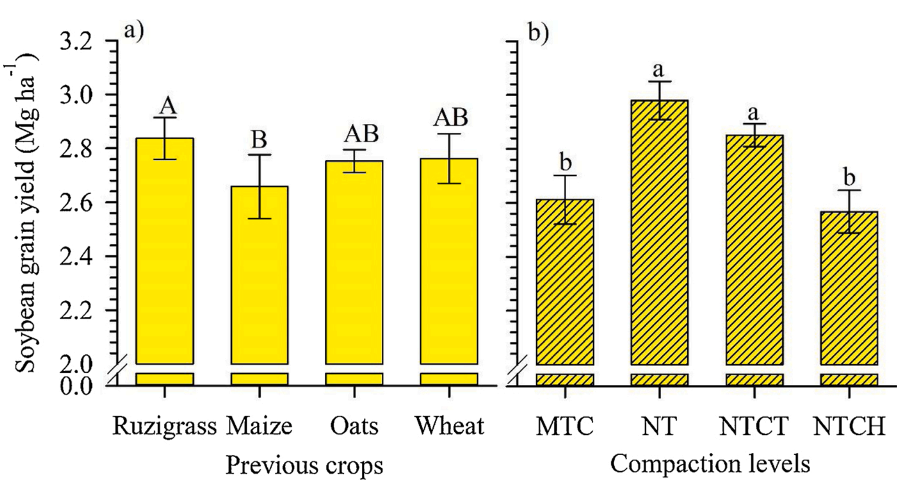

Fig. 7. Soybean grain yield after precrops (a) and different soil compaction levels (b) in an Oxisol. MTC: minimum tillage system with soil chiselling; NT: no-tillage system; NTCT: no-tillage with additionally compaction by four passes of tractor; NTCH: no-tillage with eight traffic of harvester. *Means followed by same letter do not differ by Fisher's exact test ($p < 0.10$).

Precrops significantly influenced soybean root growth (Figs. 5 and S2; Table 3) and distribution (Figs. 6 and S3) in the soil profile. In general, ruzigrass promoted greater soybean root growth compared to the other precrops evaluated under all compaction levels except under MTC. The more compacted the treatment and the deeper the soil layer, the higher the positive response of soybean root growth to ruzigrass cultivation. Increased soybean root growth and activity in crop rotations including ruzigrass under NT in Brazil was recently reported by Rosolem and Pivetta (2017). Our results indicate that the soil physical quality for root growth through the soil profile was improved by ruzigrass despite the small differences in bulk density (Fig. 2), macroporosity (Fig. 3) and water-filled porosity (Fig. S1). Furthermore, these data reinforce the low sensitivity of soil physical attributes based on mass/volume relations to management alteration (Dal Ferro et al., 2014; Moraes et al., 2016a), as previously discussed.

In Brazil, chiselling has frequently been pointed out as a strategy to disrupt compacted soil layers in areas under long-term NT (Klein and Camara, 2007; Scarpare et al., 2019). However, in the last decade, several studies have shown that soil chiselling did not increase grain yield (e.g. Franchini et al., 2012; Moraes et al., 2016a; Rosolem and Pivetta, 2017). Moreover, positive effects of chiselling on soil physical attributes (bulk density, penetration resistance and macroporosity) are short-lived, usually less than two years (Moraes et al., 2016a; Rosolem and Pivetta, 2017). In our study, soil chiselling provided lower bulk density and higher macroporosity at 0–30 cm layer in both sampling dates (February/2013 and January/2015), but did not lead to enhanced soybean grain yield (Fig. 7b) and root growth (Fig. 6). In spite of reducing mechanical stresses to roots, as a consequence of lower values of bulk density (Fig. 2) and hence SPR (Fig. 4a), soil chiselling probably increased the water stress, leading to higher overall physical limitations to soybean root growth and yield, mainly compared to NT. This affirmation is supported by the higher macroporosity (Fig. 3) and lower water-filled porosity under MTC at 20–30 cm depth (Fig. S1), indicating that chiselling reduced the soil water retention capacity. Likewise, Moraes et al. (2019a, 2018b), based on the results obtained from a long-term field experiment in a similar soil, concluded that minimum tillage with chisel plough reduced the soil water availability. In addition, chisel plough shanks break the soil mainly at its planes of weakness, producing large and compact soil blocks encompassed by cracks, large pores, small soil particles, and aggregates (Moraes et al., 2016a). Soil chiselling also results in organic matter losses and reduces soil biochemical quality (Melero et al., 2011). Unlike biopores, the pores generated by soil tillage or other non-biological processes are irregular in shape, less continuous and with few interconnections (Zhang et al., 2018); thus, non-biological pores are considered less efficient to conduct water and gases (Oades, 1993).

Water stress was described as the most limiting factor to soybean production in Southern Brazil (Sentelhas et al., 2015); therefore, increased grain yields are expected to occur in response to management practices enhancing soil water availability (Franchini et al., 2012) and deep rooting (Battisti and Sentelhas, 2017). In our study, the highest soybean grain yields were obtained under NT and after ruzigrass (Fig. 7), precisely the treatments which led to the greatest soybean root growth through the soil profile (Figs. 5 and 6) and hence, improved plant access to deep-stored water and nutrients (Han et al., 2017; Jakobsen and Dexter, 1988). The role of deep rooting to mitigate water stress impacts on soybean grain yields was clearly demonstrated in a recent study performed by Battisti and Sentelhas (2017). According to these authors, soybean with deep rooting (200 cm depth) can enhance grain yields in Brazil from 500 kg ha^{-1} up to 2500 kg ha^{-1}, depending on the water stress intensity and time of occurrence in relation to the more critical growth stage. Besides enhancing soybean rooting, improved soil structure and mulching due to ruzigrass cultivation under NT without additional compaction and mechanical disturbance (chiselling) increases water and oxygen availability to roots (Calonego and Rosolem, 2010; Moraes et al., 2018b), leading to higher soybean yields.

It has to be highlighted that the better soil structure and root growth provided by ruzigrass cultivation during a 6-month period was not enough to increase soybean yields under the most compacted treatment (NTCH) to the same level as NT, indicating a partial alleviation of compaction effects on crop growth. Accordingly, longer time is required to a complete alleviation of soil compaction constraints to soybean yields under NTCH. In contrast, soybean yields under NTCT, which is less compacted compared to NTCH, were similar to NT regardless of precrops. Thus, we can assume that combined effects of drying-wetting cycles, biopore creation and soil mulching can be resulted in complete alleviation of compaction impacts on soybean yields up to the level corresponding to NTCT after two years. These data are in agreement with Calonego et al. (2017) who concluded that the beneficial effects of cover crops on soybean performance and yield would be observed in medium to long term.

Our results demonstrate that the use of mechanical chiselling to break compacted layers resulted in soybean yield losses, at a similar rate as the most compacted treatment (NTCH) (Fig. 7). Conversely, most studies have shown that chiselling effects on soybean yields in Brazil are not significant or positive in short-term, depending on the initial compaction level (e.g. Calonego et al., 2017; Calonego and Rosolem, 2010; Franchini et al., 2012). In our study, chiselling led to bulk densities ranging from 1.05 to 1.18 Mg m^{-3} at 0–30 cm depth after precrops, regardless of their species (Fig. 2). For the same experimental area, maximum bulk density (Proctor test) was estimated at 1.52 Mg m^{-3} (Torres and Saraiva, 1999), thus resulting in a degree of compactness (Reichert et al., 2009) ranging from 69 to 77 %. These degree of compactness values are lower than the optimum for soybean yields, varying from 85 to 90 % (Reichert et al., 2009). When degree of compactness is lower than the optimum value, such as under MTC, crop yield losses are expected to occur due to three main reasons: 1) low soil-root contact (Håkansson and Lipiec, 2000; Reichert et al., 2016); 2) low unsaturated hydraulic conductivity (Håkansson and Lipiec, 2000); and 3) low water storage (Moraes et al., 2019a, 2018b, 2016a). Mechanical chiselling also disrupts pore continuity and interconnectivity, creating isolated, non-biological pores, which are less effective for water and gas conduction (Oades, 1993; Rabot et al., 2018). The final outcome of all these effects acting simultaneously is the reduction of soil water uptake and crop yields, as shown in our paper. Additionally, as already discussed, our results showed poorer soybean root growth under MTC mainly related to NT, which decisively contributes to decrease soybean yields.

5. Conclusion

It has been postulated that the crops grown from March to September (autumn/winter in Brazil), before soybean cropping season (October to February), may alleviate soil physical constraints regarding soybean root growth and grain yields. Our results greatly support these observations, once physical attributes (bulk density, macroporosity and water-filled porosity) were improved over a 2 year-period in response to combined effects of wetting-drying cycles with soil mulching and the roots of precrops. More importantly, soybean root growth (biomass and length density) and grain yields were enhanced by ruzigrass cultivation in comparison with the other precrops. In addition, the positives effects of ruzigrass on soil structure were greater as higher the initial soil compaction level in the profile. Thus, our data clearly show the high potential of ruzigrass cultivation to alleviate negative impacts of compacted soil layers on crop rooting and yield, mainly through the creation of long, continuous biopores, which reduces mechanical and water stresses to roots. These effects are expected to occur in many regions and soils with a suitable environment for ruzigrass establishment and growth.

Precrops also lead to higher soil strength, since soil penetration resistance in a given bulk density and water content was increased after two years, as a result of age-hardening phenomenon. Cover crops (ruzigrass and oats) enhance soil strength more than grain crops (maize and wheat). Soil strengthening without alterations on bulk density and pore space, together with biopores alleviating mechanical and water stresses to root growth, is here considered a fairly important process to provide higher soil resistance to aggregate disruptive forces (e.g., machinery traffic) and hence, better soil structure stability.

In spite of reducing soil mechanical impedance, our findings indicate that chiselling do not improve or even impairs soybean rooting. In addition, chiselling causes soybean yield losses in relation to non-compacted NT, which are similar to those observed in the most compacted plots. Thus, mechanical chiselling is not a suitable strategy to alleviate soil compaction effects on soybean root growth and yield in clayey Oxisols of Northern Parana State, Brazil.

Declaration of Competing Interest

The authors declare that the research titled "Precrops alleviate soil physical limitations for soybean root growth in a clayey Oxisol under no-tillage in Southern Brazil", authored by Altamir Mateus Bertollo, Moacir Tuzzin de Moraes, Julio Cezar Franchini, Amin Soltangheisi, Alvadi Antonio Balbinot Jr., Renato Levien and Henrique Debiasi, was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2020.104820.

References

Abdollahi, L., Hansen, E.M., Rickson, R.J., Munkholm, L.J., 2015. Overall assessment of soil quality on humid sandy loams: effects of location, rotation and tillage. Soil Tillage Res. 145, 29–36. https://doi.org/10.1016/j.still.2014.08.009.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil Tillage Res. 104, 1–15. https://doi.org/10.1016/j.still.2009.02.005.

Battisti, R., Sentelhas, P.C., 2017. Improvement of soybean resilience to drought through deep root system in Brazil. Agron. J. 109, 1612. https://doi.org/10.2134/agronj2017.01.0023.

Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J. Exp. Bot. 62, 59–68. https://doi.org/10.1093/jxb/erq350.

Bodner, G., Leitner, D., Kaul, H.P., 2014. Coarse and fine root plants affect pore size distributions differently. Plant Soil 380, 133–151. https://doi.org/10.1007/s11104-014-2079-8.

Böhm, W., 1979. Methods of studying root systems, biological conservation. Ecological Studies. Springer Berlin Heidelberg, Berlin. https://doi.org/10.1007/978-3-642-67282-8.

Bonetti, J., de, A., Anghinoni, I., Moraes, M.Tde, Fink, J.R., de Andrade Bonetti, J., Anghinoni, I., de Moraes, M.T., Fink, J.R., Bonetti, J., de, A., Anghinoni, I., Moraes, M.Tde, Fink, J.R., 2017. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. Soil Tillage Res. 174, 104–112. https://doi.org/10.1016/j.still.2017.06.008.

Busscher, W.J., 1990. Adjustment of flat-tipped penetrometer resistance data to a common water content. Trans. ASAE 33, 0519–0524. https://doi.org/10.13031/2013.31360.

Calonego, J.C., Rosolem, C.A., 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. Eur. J. Agron. 33, 242–249. https://doi.org/10.1016/j.eja.2010.06.002.

Calonego, J.C., Raphael, J.P.A., Rigon, J.P.G., Oliveira Neto, Lde, Rosolem, C.A., 2017. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. Eur. J. Agron. 85, 31–37. https://doi.org/10.1016/j.eja.2017.02.001.

Colombi, T., Torres, L.C., Walter, A., Keller, T., 2018. Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth – a vicious circle. Sci. Total Environ. 626, 1026–1035. https://doi.org/10.1016/j.scitotenv.2018.01.129.

Dal Ferro, N., Sartori, L., Simonetti, G., Berti, A., Morari, F., 2014. Soil macro- and microstructure as affected by different tillage systems and their effects on maize root growth. Soil Tillage Res. 140, 55–65. https://doi.org/10.1016/j.still.2014.02.003.

Engel, F.L., Bertol, I., Ritter, S.R., Paz González, A., Paz-Ferreiro, J., Vidal Vázquez, E., 2009. Soil erosion under simulated rainfall in relation to phenological stages of soybeans and tillage methods in Lages, SC. Brazil. Soil Tillage Res. 103, 216–221. https://doi.org/10.1016/j.still.2008.05.017.

FEBRAPD, 2019. Área Do Sistema Plantio Direto [WWW Document]. Fed. Bras. Plantio Direto e Irrig. URL https://febrapdp.org.br/area-de-pd (accessed 10.31.19).

Franchini, J.C., Debiasi, H., Balbinot Junior, A.A., Tonon, B.C., Farias, J.R.B., Oliveira, M.C.Nde, Torres, E., 2012. Evolution of crop yields in different tillage and cropping systems over two decades in southern Brazil. F. Crop. Res. 137, 178–185. https://doi.org/10.1016/j.fcr.2012.09.003.

Fuentes, M., Govaerts, B., De León, F., Hidalgo, C., Dendooven, L., Sayre, K.D., Etchevers, J., 2009. Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. Eur. J. Agron. 30, 228–237. https://doi.org/10.1016/j.eja.2008.10.005.

Gregory, A.S., Watts, C.W., Whalley, W.R., Kuan, H.L., Griffiths, B.S., Hallett, P.D., Whitmore, A.P., 2007. Physical resilience of soil to field compaction and the interactions with plant growth and microbial community structure. Eur. J. Soil Sci. 58, 1221–1232. https://doi.org/10.1111/j.1365-2389.2007.00956.x.

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53, 71–85. https://doi.org/10.1016/S0167-1987(99)00095-1.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009.

Han, E., Kautz, T., Perkons, U., Lüsebrink, M., Pude, R., Köpke, U., 2015. Quantification of soil biopore density after perennial fodder cropping. Plant Soil 394, 73–85. https://doi.org/10.1007/s11104-015-2488-3.

Han, E., Kautz, T., Köpke, U., 2016. Precrop root system determines root diameter of subsequent crop. Biol. Fertil. Soils 52, 113–118. https://doi.org/10.1007/s00374-015-1049-5.

Han, E., Kautz, T., Huang, N., Köpke, U., 2017. Dynamics of plant nutrient uptake as affected by biopore-associated root growth in arable subsoil. Plant Soil 415, 145–160. https://doi.org/10.1007/s11104-016-3150-4.

Jakobsen, B.E., Dexter, A.R., 1988. Influence of biopores on root growth, water uptake and grain yield of wheat (Triticum aestivum) based on predictions from a computer model. Biol. Fertil. Soils 6, 315–321. https://doi.org/10.1007/BF00261020.

Jorge, L.A.C., Silva, D.J.C.B., 2010. Safira: Manual De Utilização, 1ª ed. ed. Embrapa Istrumentação Agropecuária, São Carlos, SP.

Kautz, T., 2015. Research on subsoil biopores and their functions in organically managed soils: a review. Renew. Agric. Food Syst. 30, 318–327. https://doi.org/10.1017/S1742170513000549.

Keller, T., 2005. A Model for the Prediction of the Contact Area and the Distribution of Vertical Stress below Agricultural Tyres from Readily Available Tyre Parameters. Biosyst. Eng. 92, 85–96. https://doi.org/10.1016/j.biosystemseng.2005.05.012.

Klein, V.A., Camara, R.K., 2007. Rendimento da soja e intervalo hídrico ótimo em latossolo vermelho sob plantio direto escarificado. Rev. Bras. Ciência do Solo 31, 221–227. https://doi.org/10.1590/S0100-06832007000200004.

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1–12. https://doi.org/10.1016/j.still.2006.11.004.

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H., Vanderborght, J., 2019. Modeling the impact of biopores on root growth and root water uptake. Vadose Zone J. 18, 0. https://doi.org/10.2136/vzj2018.11.0196.

Leitner, D., Meunier, F., Bodner, G., Javaux, M., Schnepf, A., 2014. Impact of contrasted maize root traits at flowering on water stress tolerance – a simulation study. F. Crop. Res. 165, 125–137. https://doi.org/10.1016/j.fcr.2014.05.009.

McKenzie, B.M., Bengough, A.G., Hallett, P.D., Thomas, W.T.B., Forster, B., McNicol, J. W., 2009. Deep rooting and drought screening of cereal crops: a novel field-based method and its application. F. Crop. Res. 112, 165–171. https://doi.org/10.1016/j.fcr.2009.02.012.

Melero, S., Panettieri, M., Madejón, E., Macpherson, H.G., Moreno, F., Murillo, J.M., 2011. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: effect on soil quality. Soil Tillage Res. 112, 107–113. https://doi.org/10.1016/j.still.2010.12.001.

Moraes, M.T., Silva, V.Rda, Zwirtes, A.L., Carlesso, R., 2014. Use of penetrometers in agriculture: a review. Eng. Agrícola 34, 179–193. https://doi.org/10.1590/S0100-69162014000100019.

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., Bonini da Luz, F., 2016a. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. Soil Tillage Res. 155, 351–362. https://doi.org/10.1016/j.still.2015.07.015.

Moraes, M.T., Debiasi, H., Franchini, J.C., Silva, V.Rda, 2016b. Benefícios das plantas de cobertura sobre as propriedades físicas do solo. In: Tiecher, T. (Ed.), Manejo e conservação do solo e da água em pequenas propriedades rurais no sul do Brasil: Práticas alternativas de manejo visando a conservação do solo e da água. UFRGS, Porto Alegre, pp. 34–48. http://hdl.handle.net/10183/149123.

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.Rda, Luz, F.Bda, 2017. Age-hardening phenomena in an oxisol from the subtropical region of Brazil. Soil Tillage Res. 170, 27–37. https://doi.org/10.1016/j.still.2018.09.009.

Moraes, M.T., Bengough, A.G., Debiasi, H., Franchini, J.C., Levien, R., Schnepf, A., Leitner, D., 2018a. Mechanistic framework to link root growth models with weather and soil physical properties, including example applications to soybean growth in Brazil. Plant Soil 428, 67–92. https://doi.org/10.1007/s11104-018-3656-z.

Moraes, M.T., Debiasi, H., Franchini, J.C., 2018b. Modelling of soil water dynamics under tillage systems in a Rhodic Eutrudox. Sci. Agrar. 19, 142–152. https://doi.org/10.5380/rsa.v19i1.52216.

Moraes, M.T., Debiasi, H., Franchini, J.C., Bonetti, J., de, A., Levien, R., Schnepf, A., Leitner, D., 2019a. Mechanical and hydric stress effects on maize root system development at different soil compaction levels. Front. Plant Sci. 10, 1358. https://doi.org/10.3389/fpls.2019.01358.

Moraes, M.T., Luz, F.Bda, Debiasi, H., Franchini, J.C., 2019b. Soil load support capacity increases with time without soil mobilization as a result of age-hardening phenomenon. Soil Tillage Res. 186, 128–134. https://doi.org/10.1016/j.still.2018.09.009.

Naveed, M., Brown, L.K., Raffan, A.C., George, T.S., Bengough, A.G., Roose, T., Sinclair, I., Koebernick, N., Cooper, L., Hackett, C.A., Hallett, P.D., 2017. Plant exudates may stabilize or weaken soil depending on species, origin and time. Eur. J. Soil Sci. 68, 806–816. https://doi.org/10.1111/ejss.12487.

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015. Mitigation of clayey soil compaction managed under no-tillage. Soil Tillage Res. 148, 119–126. https://doi.org/10.1016/j.still.2014.12.007.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56, 377–400. https://doi.org/10.1016/0016-7061(93)90123-3.

Ortigara, C., 2017. Physical and Hydric Properties of a Rhodic Eutrudox in Different Long-term Crop Systems. Master Dissertation. Federal University of Santa Maria, Frederico Westphalen, p. 75 (in Portuguese, with English abstract).

Perkons, U., Kautz, T., Uteau, D., Peth, S., Geier, V., Thomas, K., Lütke Holz, K., Athmann, M., Pude, R., Köpke, U., 2014. Root-length densities of various annual crops following crops with contrasting root systems. Soil Tillage Res. 137, 50–57. https://doi.org/10.1016/j.still.2013.11.005.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137. https://doi.org/10.1016/j.geoderma.2017.11.009.

Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., Horn, R., Håkansson, I., 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102, 242–254. https://doi.org/10.1016/j.still.2008.07.002.

Reichert, J.M., da Rosa, V.T., Vogelmann, E.S., da Rosa, D.P., Horn, R., Reinert, D.J., Sattler, A., Denardin, J.E., 2016. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil Tillage Res. 158, 123–136. https://doi.org/10.1016/j.still.2015.11.010.

Romero-Ruiz, A., Linde, N., Keller, T., Or, D., 2018. A review of geophysical methods for soil structure characterization. Rev. Geophys. 56, 672–697. https://doi.org/10.1029/2018RG000611.

Rosolem, C.A., Pivetta, L.A., 2017. Mechanical and biological approaches to alleviate soil compaction in tropical soils: assessed by root growth and activity (Rb uptake) of soybean and maize grown in rotation with cover crops. Soil Use Manag. 33, 141–152. https://doi.org/10.1111/sum.12313.

SAS Institute Inc, 2013. SAS Enterprise Guide.

Scarpare, F.V., de Jong van Lier, Q., de Camargo, L., Pires, R.C.M., Ruiz-Corrêa, S.T., Bezerra, A.H.F., Gava, G.J.C., Dias, C.T.S., 2019. Tillage effects on soil physical condition and root growth associated with sugarcane water availability. Soil Tillage Res. 187, 110–118. https://doi.org/10.1016/j.still.2018.12.005.

Schjønning, P., Lamandé, M., 2010. A note on the vertical stresses near the soil-tyre interface. Soil Tillage Res. 108, 77–82. https://doi.org/10.1016/j.still.2010.03.006.

Sentelhas, P.C., Battisti, R., Câmara, G.M.S., Farias, J.R.B., Hampf, A.C., Nendel, C., 2015. The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production. J. Agric. Sci. 153, 1394–1411. https://doi.org/10.1017/S0021859615000313.

Shampine, L.F., 2008. Vectorized adaptive quadrature in MATLAB. J. Comput. Appl. Math. 211, 131–140. https://doi.org/10.1016/j.cam.2006.11.021.

Silva, A.P., Babujia, L.C., Franchini, J.C., Souza, R.A., Hungria, M., 2010. Microbial biomass under various soil- and crop-management systems in short- and long-term experiments in Brazil. F. Crop. Res. 119, 20–26. https://doi.org/10.1016/j.fcr.2010.06.012.

Silva, A.Pda, Babujia, L.C., Franchini, J.C., Ralisch, R., Hungria, M., Guimarães, Mde F., 2014. Soil structure and its influence on microbial biomass in different soil and crop management systems. Soil Tillage Res. 142, 42–53. https://doi.org/10.1016/j.still.2014.04.006.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de métodos de análise de solo, 3a ed. ed, Manuel d'utilisation, Embrapa Solos, Brasilia, DF.

Tivet, F., De Moraes Sá, J.C., Lal, R., Borszowskei, P.R., Briedis, C., dos Santos, J.B., Sá, M.F.M., da Cruz Hartman, D., Eurich, G., Farias, A., Bouzinac, S., Séguy, L., 2013. Soil organic carbon fraction losses upon continuous plow-based tillage and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Geoderma 209–210, 214–225. https://doi.org/10.1016/j.geoderma.2013.06.008.

Torres, E., Saraiva, O.F., 1999. Camadas de impedimento mecânico do solo em sistemas agrícolas com a soja. Embrapa Soja, Circular Técnica. CNPSo, Londrina, p. 58.

Utomo, W.H., Dexter, A.R., 1981. Age hardening of agricultural top soils. J. Soil Sci. 32, 335–350. https://doi.org/10.1111/j.1365-2389.1981.tb01710.x.

Williams, S.M., Weil, R.R., 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68, 1403–1409. https://doi.org/10.2136/sssaj2004.1403.

Wuest, S.B., 2001. Soil biopore estimation: effects of tillage, nitrogen, and photographic resolution. Soil Tillage Res. 62, 111–116. https://doi.org/10.1016/S0167-1987(01)00218-5.

Yu, Y., Loiskandl, W., Kaul, H.-P., Himmelbauer, M., Wei, W., Chen, L., Bodner, G., 2016. Estimation of runoff mitigation by morphologically different cover crop root systems. J. Hydrol. 538, 667–676. https://doi.org/10.1016/j.jhydrol.2016.04.060.

Zhang, Z., Liu, K., Zhou, H., Lin, H., Li, D., Peng, X., 2018. Three dimensional characteristics of biopores and non-biopores in the subsoil respond differently to land use and fertilization. Plant Soil 428, 453–467. https://doi.org/10.1007/s11104-018-3689-3.